PATENT APPLICATION

METHOD TO ACHIEVE LOW AND STABLE FERROMAGNETIC COUPLING FIELD

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FIELD OF THE INVENTION

This invention relates generally to spin valves. More particularly, it relates to the coupling field of spin valves.

BACKGROUND ART

A spin valve or a magnetoresistive (MR) sensor detects magnetic field signals through the resistance changes of a read element, fabricated of a magnetic material, as a function of the strength and direction of magnetic flux being sensed by the read element. The conventional MR sensor operates on the basis of the anisotropic magnetoresistive (AMR) effect in which a component of the read element resistance varies as the square of the cosine of the angle between the magnetization in the read element and the direction of sense current flow through the read element. Such a MR Sensor can be used to read data from a magnetic medium. An external magnetic field from the magnetic medium (the signal field) causes a change in the direction of magnetization in the read element, which in turn causes a change in resistance ($\Delta R/R$) in the read element and a corresponding change in the sensed current or voltage.

A spin valve has been identified in which the resistance between two uncoupled ferromagnetic layers varies as the cosine of the angle between the magnetizations of the two layers and is independent of the direction of current flow.

An external magnetic field causes a variation in the relative orientation of the magnetization of neighboring ferromagnetic layers in a spin valve. This in turn causes a change in the spin-dependent scattering of conduction electrons and thus the electrical resistance of the spin valve. The resistance of the spin valve thus changes as the relative alignment of the magnetizations of the ferromagnetic layers changes.

Typically, a conventional simple spin valve comprises a ferromagnetic free layer, a spacer layer, and a single-layer pinned ferromagnetic layer, which is exchange-coupled with an anti-ferromagnetic (AF) layer. In an anti-parallel (AP) pinned spin valve, the single-layer pinned ferromagnetic layer is replaced by a laminated structure comprising at least two ferromagnetic pinned sublayers separated by one or more thin non-ferromagnetic anti-coupling sublayers.

In general, the larger the value of $\Delta R/R$ and the smaller the coupling field H_f, the better the performance of the spin value. The $\Delta R/R$ value of a spin valve conventionally increases as the thickness of the spacer layer decreases due to the reduced shunting of the sense current in the spacer layer of the spin valve. For example, a spin valve with a copper spacer layer having a thickness of 28Å will achieve a $\Delta R/R$ of about 5%. If the thickness of copper spacer is reduced to 20Å, a $\Delta R/R$ of 8% will be obtained. However, the ferromagnetic coupling field H_f also increases as the thickness of the spacer layer decreases. In addition, the ferromagnetic coupling field of conventional spin valves is unstable upon annealing cycles. For example, the ferromagnetic coupling field of spin valves changes from about +5 Oe at the beginning of the annealing process to +20 Oe after annealing cycles.

An article entitled "Oxygen as a Surfactant in the Growth of Giant Magnetoresistance Spin Valve" published Dec. 15, 1997 by Journal of Applied Physic to Egelhoff et al. discloses a method for increasing the giant magnetoresistance of $\Delta R/R$ of Co/Cu spin valves with use of oxygen. In this method, oxygen is introduced in an ultrahigh vacuum deposition chamber with an oxygen partial pressure of 5×10^{-9} Torr during deposition of the spin valve layers, or the top copper surface is exposed to the oxygen to achieve an oxygen coverage, after which growth of the sample is completed. The oxygen acts as a surfactant during film growth to suppress defects and to create a surface that scatters electrons more specularly. Oxygen coverage decreases the ferromagnetic coupling between magnetic layers, and decreases the sheet resistance of spin valves.

Unfortunately, this technique requires a very small oxygen partial pressure window around $5x10^{-9}$ Torr, since when the oxygen partial pressure is increased to only 10^{-8} Torr, all GMR ($\Delta R/R$) gain due to oxygen is lost, and at oxygen pressures higher than this, the fall-off in GMR is rapid. This very small oxygen partial pressure is very difficult to achieve or to maintain in a large manufacturing type system. Also, oxygen exposure of only one surface of the copper spacer layer does not optimize the ferromagnetic coupling field. Furthermore, the use of oxygen for all spin valve layer depositions may result in oxidation of Mn in anti-ferromagnetic materials, such as FeMn, PtMn, IrMn, PdPtMn and NiMn, and thus kills the spin valve effect. Therefore this technique can not be applied for spin valve deposition.

In addition, adsorbing oxygen only on the copper surface does not improve the GMR, and produces only a positive coupling field. Furthermore, this technique results in a decrease in sheet resistance, which reduces the overall signal. Finally, prior art oxygen treatment does not show stabilization of the ferromagnetic coupling field upon hard bake annealing cycles.

There is a need, therefore, for an improved method of making spin valves that overcomes the above difficulties.

OBJECTS AND ADVANTAGES

Accordingly, it is a primary object of the present invention to provide spin valves with low and stable coupling field H_f.

It is a further object of the invention to provide spin valves with high magnetoresistive ratio $\Delta R/R$.

It is another object of the invention to develop a process of making spin valves with oxygen partial pressure levels can be used in manufacturing systems.

It is another object of the invention to develop a process of making spin valves achieving negative coupling fields in production processes.

It is a further object of the invention to develop a process of making spin valves, which does not result in reduction in sheet resistance.

It is another object of the invention to develop a process of making spin valves, which can be used with metallic anti-ferromagnetic materials or oxide in addition to oxide antiferromagnetic materials.

It is an additional object of the invention to provide a method of making spin valves having the above properties, which can be applied for bottom and top spin valves.

SUMMARY

These objects and advantages are attained by spin valves having a first surface of one ferromagnetic layer and a second surface of a spacer layer, treated with oxygen.

According to a first embodiment of the present invention, a simple spin valve includes a ferromagnetic layer having a first surface, such as a ferromagnetic free layer, and a spacer layer having a second surface. One or more of the first and second surfaces has been treated with oxygen after deposition of the corresponding layers and oxygen treatment has been shut off before depositing a subsequent layer. Treatment with oxygen herein refers to exposing a surface of a layer of material to oxygen after the layer has been deposited. Physisorbed oxygen on these surfaces limits the intermixing between the layers and reduces the surface roughness of the surfaces. As a result, the coupling field is reduced. The obtained coupling field is around -10 Oe for about 20Å copper, and the coupling field is stable upon hard bake annealing cycles at 232°C for 11 hours or at 270°C for 6 hours. Furthermore, the magnetoresistive ratio $\Delta R/R$ is enhanced from about 6% to about 9%.

According to a second embodiment of the present invention, a bottom AP-pinned spin valve includes a first surface of a ferromagnetic layer, which is an AP-pinned sublayer, and a second surface of a spacer layer, treated with oxygen. The effect of oxygen surface treatment in AP-pinned spin valves is similar to the effect of oxygen surface treatment in simple spin valve as described in the first embodiment.

A method of making spin valves having surfaces treated with oxygen is described in a third embodiment of the present invention. An ion beam sputtering technique may be used to make the spin valves. A substrate is provided in a vacuum chamber. A first ferromagnetic layer, which may be a free layer for a top spin valve or a pinned layer for a bottom spin valve, is deposited onto the substrate. A first surface of the first ferromagnetic layer is exposed to an oxygen-rich atmosphere with oxygen partial pressure of between about $1x10^{-7}$ Torr and about $5x10^{-5}$ Torr, by introducing an oxygen burst into the vacuum chamber for about 30 seconds. The oxygen molecules are directed toward the substrate, and a substrate shutter is fully open to directly expose the oxygen beam. Oxygen is physisorbed on the first surface. After about 30 seconds, the oxygen is shut off, and the normal process of fabrication of the spin valve is resumed. A spacer layer of about 20Å thick is deposited on the oxygen treated surface. A second oxygen burst is introduced into the vacuum chamber with an oxygen partial pressure of about $5x10^{-6}$ Torr for treating a second surface of the spacer layer. The process of treating this second surface is similar to the process of treating the first surface as described above. The oxygen is again shut off before a second ferromagnetic layer, which may be a pinned layer for a top spin valve or a free layer bottom spin valve, is subsequently deposited..

The method described in the third embodiment may be used for top and bottom simple spin valves, top and bottom AP-pinned spin valves, and dual spin valves.

According to a third embodiment of the present invention, spin valves of the types depicted in the first and second embodiments, which are made by the method described in the third embodiment, are incorporated in a GMR read/write head. The GMR read/write head includes a lower shield layer and an upper shield layer, which sandwich a spin valve, a lower gap disposed between the lower shield and the spin valve, and an upper gap disposed between the upper shield and the spin valve. The spin valve converts a magnetic signal to an electrical signal by using the magnetoresistive effect generated by a relative angle between magnetizing directions of a ferromagnetic free layer and a ferromagnetic pinned layer.

A GMR read/write head of the type depicted in the fourth embodiment is incorporated in a disk drive system including a magnetic recording disk, a motor for spinning the magnetic recording disk, the read/write head and an actuator for moving the read/write head across the magnetic recording disk, according to a fifth embodiment of the present invention.

BRIEF DESCRIPTION OF THE FIGURES

Fig. **1** is a cross-sectional schematic diagram of a top simple spin valve according to a first embodiment of the present invention;

Fig. **2** is a cross-sectional schematic diagram of a bottom AP-pinned spin valve according to a second embodiment of the present invention;

Figs. **3A-F** are cross-sectional schematic diagrams illustrating the steps of a process making spin valves with low and stable coupling field according to a third embodiment of the present invention;

Fig. **4** is a graph illustrating a plot of roughness as a function of oxygen flow with copper spacer thickness of 20Å for an AP-pinned spin valve;

Fig. **5** is a graph illustrating a plot of sheet resistance as a function of oxygen flow with the copper spacer layer thickness of 20Å for an AP-pinned spin valve;

Fig. **6** is a graph illustrating a plot of magnetoresistive ratio $\Delta R/R$ as a function of oxygen flow with the copper spacer layer thickness of 20Å for an AP-pinned spin valve;

Fig. **7** is a graph illustrating a plot of coupling field as a function of oxygen flow with the copper spacer layer thickness of 20Å for an AP-pinned spin valve;

Fig. **8** is a graph illustrating a plot of coercive field as a function of oxygen flow with the copper spacer layer thickness of 20Å for an AP-pinned spin valve;

Fig. **9** is a graph depicting plots illustrating the properties of AP-pinned spin valves as functions of copper spacer layer deposition time with a constant oxygen flow of 2sccm;

Fig. **10** is a graph depicting only two plots of magnetoresistive ratio ($\Delta R/R$) and coupling field H_f as functions of copper spacer layer deposition time illustrated in Fig. 9;

Fig. **11** is a schematic diagram of a GMR read/write head according to a fourth embodiment of the present invention; and

Fig. **12** is a schematic diagram of a disk drive system according to a fifth embodiment of the present invention.

DETAILED DESCRIPTION

Although the following detailed description contains many specifics for the purposes of illustration, anyone of ordinary skill in the art will appreciate that many variations and alterations to the following details are within the scope of the invention. Accordingly, the following preferred embodiment of the invention is set forth without any loss of generality to, and without imposing limitations upon, the claimed invention.

Fig. 1 is a cross-sectional schematic diagram illustrating a layer structure of a top simple spin valve **100** according to a first embodiment of the present invention. The spin valve **100** includes a ferromagnetic free layer **105** including a ferromagnetic layer **106** contacting a nanolayer **108** having a first surface **109**, a ferromagnetic pinned layer **112**, and a spacer layer **110**, which has a second surface **111**, disposed between the ferromagnetic free layer **105** and the ferromagnetic pinned layer **112**. The spin valve **100** may further include an anti-ferromagnetic (AF) layer **114**, disposed between the ferromagnetic pinned layer **112** and a cap layer **116**, and a oxide seed layer **104** proximate the ferromagnetic free layer **105**. The nanolayer **108** enhances the magnetoresistive ratio ($\Delta R/R$) for the spin valve **100**.

Ferromagnetic layer **106** typically includes a material containing Ni, Fe, Co or alloys of Ni, Fe and Co such as NiFe, NiCo, and FeCo. The ferromagnetic pinned layer **112** is typically made of Co or CoFe. The spacer layer **110** is typically made of Cu, Ag, Au or their alloys. The AF layer **114** typically includes a material containing Mn, such as FeMn, PtMn, IrMn, PdPtMn and NiMn. The nanolayer **108** is typically made of CoFe, and the cap layer **116** typically includes Ta. Oxide seed layer **104** is typically made of NiMnO.

The first surface **109** and the second surface **111** are treated with oxygen during an ion beam sputtering process of making the spin valve **100**. The oxygen treatment of the surface **109** or **111** occurs after the deposition of the corresponding layer **108** or **110**. The first surface **109** may be exposed to oxygen after nanolayer **108** has been deposited. Similarily the second surface **111** may be exposed to oxygen after the spacer layer **110** has been deposited. Oxygen exposure may be restricted during the deposition of nanolayer **108** and spacer layer **110**. Oxygen treated surfaces **109** and **111** limit the intermixing between the nanolayer **108** and the spacer layer **110**, and between the spacer layer **110** and the pinned layer **112** respectively. By treating the surface with oxygen after deposition of the corresponding layers, higher oxygen partial pressures may be used compared to the oxygen partial pressures previously used when treating layers with oxygen during deposition. Consequently, spin valves such as spin valve **100** may be fabricated with existing manufacturing type deposition equipment. Furthermore, if oxygen exposure is restricted after deposition, oxygen sensitive layers, such as Mn containing layers, will not be undesirably exposed to the risk of oxidation.

These oxygen treated surfaces **109** and **111** reduce the surface roughness, therefore the ferromagnetic coupling H_f of the spin valve **100** is reduced. The obtained coupling field H_f of spin valve **100** is between about -10 Oe and about +10 Oe, which is stable upon the hard bake annealing cycles at 232°C for 11 hours, or at 270°C for 6 hours. In addition, the magnetoresistive ratio $\Delta R/R$ of spin valve 100 is also enhanced from about 6% to about 9%.

Fig. 2 is a cross sectional schematic diagram illustrating a layer structure of a bottom AP-pinned spin valve **200** according to a second embodiment of the present invention. The AP-pinned spin valve **200** includes a ferromagnetic free layer **205** including a ferromagnetic layer **206** contacting a nanolayer **208**, an AP ferromagnetic pinned layer **212**, and a spacer layer **210** located between the ferromagnetic free layer **205** and the AP-pinned layer **212**. The AP-pinned spin valve **200** further includes an AF layer **214** disposed between the AP-pinned layer **212** and a metal seed layer **216**, two oxide seed layer **202** and **204** under the metal seed layer **216**, and a cap layer **218** disposed on top of the ferromagnetic free layer **206**. The material of each layer of AP-pinned spin valve **200,** except the AP-pinned layer **212** and the oxide seed layer **202**, is similar to those of the corresponding layers of the simple spin valve **100** as described in Fig. 1. The oxide seed layer **202** is typically made of Al_2O_3.

The AP-pinned layer **212** includes a first ferromagnetic pinned sublayer **220**, a second ferromagnetic pinned sublayer **224**, and an anti-parallel (AP) pinned spacer sublayer **222** between the first pinned sublayer **220** and the second pinned sublayer **224**. Two ferromagnetic pinned sublayers **220** and **224** are typically made of CoFe, the AP pinned spacer sublayer **222** is typically made of Ru, Cr, Rh or Cu, or their alloys.

The second ferromagnetic pinned sublayer **224** includes a first surface **211**, and the spacer layer **210** has a second surface **209**. In this embodiment the first surface **211** corresponds to ferromagnetic pinned sublayer **224** and the second surface **209** corresponds to the spacer layer **210**. The first and the second surfaces **211** and **209** are treated with oxygen after depositing corresponding layers **224** and **210** . The oxygen treatment generally takes place during the fabrication of the AP-pinned spin valve **200**. The effect of oxygen treated surfaces **209** and **211** on the roughness and the coupling field H_f of AP-pinned spin valve **200** is similar to the effect of oxygen treated surfaces **109** and **111** of simple spin valve **100** as described in Fig. 1. The coupling field H_f of AP-pinned spin valve **200** is around -10 Oe, and the magnetoresistive ratio $\Delta R/R$ of AP-pinned spin valve **200** is enhanced from about 5.5% and 7.7%.

An ion beam sputtering method may be used to produce spin valves of the types depicted in Figs. 1 and 2 to easily control the deposition between wafers or within a wafer. An exemplary sputtering method is disclosed in US. Pat. No. 5,871,622 issued Feb.16, 1999 and U.S. Pat. No. 5,492,605 issued Feb. 20, 1996 by the inventor. Figs. 3A-F are cross-sectional schematic diagrams illustrating the steps of making spin valves of the types depicted in Figs. 1 and 2. As shown in Fig. 3A, a first ferromagnetic layer **304** is deposited on a substrate **302** in a vacuum chamber. First ferromagnetic layer **304** may be a free layer for a top spin valve or a pinned layer for a bottom spin valve. A first oxygen burst is introduced in to the vacuum chamber with oxygen partial pressure of about $5x10^{-6}$Torr. A first surface **305** of the first ferromagnetic layer **304** is exposed to this oxygen-rich atmosphere. Oxygen molecules are directed toward the substrate **302** and the substrate shutter, which is not shown in Fig. 3A, is fully open to directly expose first surface **305** to the oxygen. As a result, oxygen is physisorbed on the first surface **305** to produce a first oxgen treated surface **306**.

An oxygen valve controlling the flow of oxygen to the chamber is then shut to reduce the oxygen partial pressure. After the oxygen valve is shut, the deposition process resumes. A spacer layer **308** is deposited on the first oxygen treated surface **306** which is shown in Fig. 3B. The spacer layer **308** is deposited over the oxygen treated surface **306** for approximately 30 seconds and has a thickness of about 20Å. The spacer layer **308** has a second surface **309** that is treated with oxygen using a method similar to the method of treating the first surface **305** with oxygen as described in Fig. 3A. As shown in Fig. 3C, the second surface **309** is exposed in an oxygen partial pressure of about $5x10^{-6}$ Torr, and oxygen is physisorbed on the second surface **309** to produce a second oxygen treated surface **310**. Note that the oxygen treatment of surfaces **305** and **309** take place after the deposition of the corresponding layers **304** and **308.** After the oxygen valve is shut off again a second ferromagnetic layer **312**, e.g., a ferromagnetic pinned layer for a top spin valve or a ferromagnetic free layer for a bottom spin valve , is subsequently deposited onto the second oxygen treated surface **310** as shown in Fig. 3D.

The process of making the spin valve **300** as described in Figs. 3A-D does not require any additional steps to incorporate the oxygen burst into the standard spin valve of the prior art. This process may be used for top and bottom simple spin valves, top and bottom AP-pinned spin valves, and dual spin valves.

Experimental Results

An example is given below to show the oxygen exposure of different surfaces and how it affects the coupling field H_f of simple top spin valves. A simple spin valve generally includes an oxide seed layer of NiMnO 30Å thick, a free layer including a ferromagnetic layer of NiFe 45Å thick and a nanolayer of CoFe 15Å thick, a spacer layer of Cu 20Å thick, a pinned layer of CoFe 24Å thick, an AF layer of IrMn 80Å thick, and a cap layer of Ta 50Å thick. Table 1 below shows the properties of two simple spin valves A and B, which have the same structure as described, except for the oxygen exposed surfaces. In spin valve A only the surface of Cu spacer layer, corresponding to layer **111** of Fig. 1, has been exposed to oxygen as described above. In spin valve B, the surfaces of the CoFe layer and Cu spacer layer, corresponding to surfaces **109** and **111** in Fig. 1, have been treated with oxygen.

TABLE 1

	Spin valve A	Spin valve B
$\Delta R/R$ (%)	8.32	8.35
R (Ohms/sq)	20	20
H_f(Oe)	16	6.5
H_c (Oe)	4	5

The data in the Table 1 shows that the coupling field H_f is about 2.5 times smaller when the spin valve has oxygen exposure of both Cu and CoFe surfaces compared to when the spin valve has oxygen exposure of the Cu surface only. The coupling field H_f of simple spin valve B does not degrade upon hard bake annealing at 232°C. Indeed the spin valve B, which was annealed at 232°C for 11 hours or at 270°C for 6 hours, maintained a coupling field at around 8 Oe.

The effect of oxygen surface treatment as described in Figs. 2-3 on the properties of bottom AP-pinned PtMn spin valves is shown in Figs 4-9. A bottom AP pinned PtMn spin valve generally includes a first oxide seed layer of Al_2O_3 30Å thick, a second oxide seed layer of NiMnO 30Å thick, a metal seed layer of Ta 35Å thick, an AF layer of PtMn 250Å thick, a first pinned sublayer of CoFe 17Å thick, an AP pinned spacer sublayer of Ru 8Å thick, a second pinned sublayer of CoFe 26Å thick, a spacer layer of Cu 20Å thick, a free layer including a ferromagnetic layer of NiFe 45Å thick and a nanolayer of CoFe 15Å thick, and a cap layer of Ta 50Å thick. Figs. 4-8 are plots of the surface roughness Ra, coupling field H_f, sheet resistance R, magnetoresistive ratio $\Delta R/R$, and coercive field H_c as functions of oxygen flow for an AP-pinned spin valve of the type depicted in Fig. 2. The spin valve in Figs. 4-8 has a spacer layer about 20Å thick. As shown in Fig. 4, the surface roughness Ra is typically about 2.9Å when the first and second surfaces are not treated with oxygen. The surface roughness Ra decreases from about 2.9Å to a minimum value of about 1.75Å as the oxygen flow increases from zero to about 2sccm. After this point, the surface roughness Ra increases as the oxygen flow increases. Therefore, the surface roughness is minimized at an oxygen flow of about 2sccm.(e.g. $5x10^{-6}$ Torr oxygen partial pressure)

As shown in Fig. 5, the sheet resistance of an AP-pinned spin valve without oxygen surface treatment is typically about 19 Ohms/sq, which does not vary much as the oxygen flow increases. The sheet resistance typically stays constant when the oxygen flow is in a range of from about 1.5sccm to about 3sccm. The sheet resistance R is typically about 19 Ohms/sq for an oxygen flow of about 2sccm.

The improvements of the magnetoresistive ratio $\Delta R/R$ and the coupling field H_f of an AP-pinned spin valve are shown in Figs 6. and 7 respectively. The magnetoresistive ratio $\Delta R/R$ is typically about 6% with a coupling field H_f of about 56 Oe when the first and second surfaces of the AP spin valve are not treated with oxygen. $\Delta R/R$ increases to about 7.6%, and the coupling field H_f decreases rapidly to about 17 Oe as the oxygen flow is typically about 0.5sccm. The coupling field decreases from about 17 Oe to about -11 Oe, while $\Delta R/R$ of about 7.6% does not vary as the oxygen flow increases from about 0.5sccm to about 2.5sccm. After this point, $\Delta R/R$ typically decreases and the coupling field H_f typically increases as the oxygen flow increases. The coupling field H_f is about -9 Oe for an oxygen flow of about 2sccm.

In Fig. 8, the coercive field H_c decreases from about 6 Oe to about 5 Oe as the oxygen flow increases from zero to about 0.5sccm. After that, the coercive field slowly increases as the oxygen flow increases. The maximum value of Hc is typically about 7 Oe obtained as an oxygen flow of about 3.5sccm. The coercive field H_c rapidly drops down to about 2 Oe when the oxygen flow is greater than 3.5sccm.

Fig. 9 is a graph illustrating the plots of magnetoresistive ratio $\Delta R/R$, sheet resistance R, coupling field H_f, and coercive field H_c as functions of spacer layer deposition time with an oxygen flow of about 2sccm. In this case, the spacer layer is made of copper. As shown in Fig. 9, the coupling field H_f rapidly decreases from about 39 Oe to about -5 Oe as the copper deposition time increases from about 25 seconds to about 30 seconds. The copper deposition rate is typically about 0.65Å/ second. After about 30 seconds the coupling field H_f typically increases as the copper deposition time increases. The minimum value of H_f, which is typically about -5 Oe is obtained after copper is deposited for about 30 seconds. The sheet resistance R of about 19 Ohms/sq, the magnetoresistive ratio $\Delta R/R$ of about 7.6%, and the coercive field H_c of 6 Oe are obtained when the deposition of the copper spacer layer is between about 25 seconds to 34 seconds. Fig. 10 is a graph illustrating the plots of coupling field H_f and magnetoresistive ratio $\Delta R/R$, which are depicted in Fig. 9, for the sake of clarity.

Spin valves of the types described above with respect to Figs. 1, 2 and 3D may be incorporated into a GMR read/write head **404** as shown in Fig. 11. The GMR read/write head **404** includes a first shield **403** and second shield **409** sandwiching a spin valve **401**. The GMR read/write head **404** further includes a first gap **405** between the first shield **403** and the spin valve **401**, and a second gap **407** between the second shield **409** and the spin valve **401**. Spin valve **401** converts a magnetic signal to an electrical signal by using the magnetoresistive effect generated by a relative angle between magnetization directions of at least two ferromagnetic layers of spin valve **401**.

The GMR read/write head depicted in Fig. 11 may be incorporated into a disk drive system **400** as shown in Fig. 12. The disk drive system **400** generally comprises a magnetic recording disk **402,** a GMR read/write head **404** containing a spin valve **401**, an actuator **406** connected to the read/write head **404,** and a motor **408** connected to the disk **402**. The motor **408** spins the disk **402** with respect to read/write head **404**. The actuator **406** moves the read/write head **404** across the magnetic recording disk **402** so the read/write head **404** may access different regions of magnetically recorded data on the magnetic recording disk **402**.

It will be clear to one skilled in the art that the above embodiment may be altered in many ways without departing from the scope of the invention. Accordingly, the scope of the invention should be determined by the following claims and their legal equivalents.